CWSF Radar for Detecting Small UAVs

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***Abstract*— Since the number of flying small unmanned aerial vehicles (UAV) is expected to increase dramatically in the next years, their radar detection has become a priority. In this paper Continuous Wave Step Frequency (CWSF) is evaluated as possible modulation for radar sensors aimed to detect small quadcopters at short range.**

Keywords — continuous wave step frequency, radar, unmanned aerial vehicles

I. INTRODUCTION

Currently small unmanned aerial vehicles (UAV) pose a serious threat for the safety of flights. Worldwide the Aviation Authorities are dealing with this issue. Recently (October 2015), the USA Federal Aviation Administration has given permission to test anti-drone technology that would counter rogue drones flying within a five-mile radius of select airports [1]. Safety of airports is not the only problem that the increasing number of flaying UAVs can pose. A critical issue is to prevent UAVs being used for terrorist attacks, espionage or other malicious activities against sites with critical infrastructures. Last but not least, UAVs flying in private area pose privacy concerns [2].

Radar can appear the technology of choice for detecting them, but standard air defense is ill prepared for UAV detection: the radar cross section of a small UAV can be smaller then 0.03m^2[3], they are low-velocity aircrafts flying in a high-clutter environment.

Continuous Wave Step Frequency (CWSF) radars are largely used in short range applications: as level gauge [4], ground penetrating radar [5], ground-based synthetic aperture radar [6]. They are not suitable for medium or long-range detections, but they can have a role in UAV detection. The aim of this article is to evaluate the potential of CWSF for detecting small UAV like quadcopters

II. CWSF RADAR

A CWSF radar transmits step-by-step a ramp of N_f frequencies in a sweep time τ, as shown in Fig. 1 For each i-th frequency it acquires the in-phase (I_i) and quadrature (Q_i) components of the back-scattered wave, so a single measurement gives a vector of N_f complex numbers: $E_i = I_i + jQ_i$.

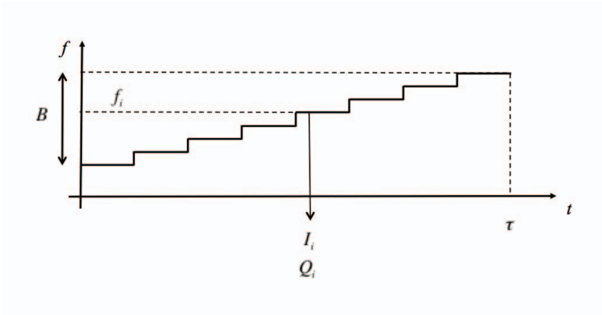

Fig. 1: Continuous Wave Step Frequency

The IFFT of the vector gives the plot in time, with peaks corresponding to the targets in the field of view. The range resolution ΔR and the unambiguous range R_U are given by

$$\Delta R = \frac{c}{2B} \qquad R_U = \frac{c}{2\Delta f} \tag{1}$$

The tone time Δt, i.e. the duration of a single frequency, has to be much more larger then the round-trip time from the farthest target (this is the reason because the CWSF is not used in long range applications).

In the following, we assume a CWSF radar operating with central frequency f_c =17 GHz, bandwidth B = 398 MHz, N_f = 798, τ = 8 ms. These are the parameters we used in experimental section of this paper.

III. PHYSICAL MODEL OF THE UAV

As first approximation, we model a quadcopter as four couples of rotating points (Fig. 2).

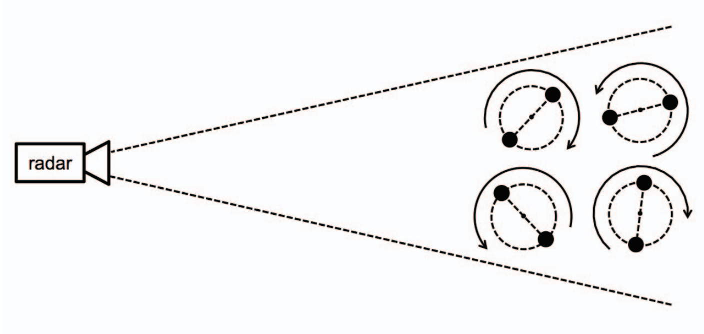

Fig. 2: Physical model

A typical small quadcopter has cruise rotation speed equal to 100 Hz and blade diameter 25 cm. It means a maximum linear speed v = 7.9 m/s, that gives a shift Doppler of 445 Hz.

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Since the tone duration is τ = 8ms, the cut-off frequency of the acquisition low-pass filter has to be larger then 99.8 kHz, that is much higher than Doppler shift. So in simulation we can assume the target static during the acquisition of a single tone. With these assumptions, the signal due to a single blade (modelled as a couple of points) can be written as

$$E_i = E_0\left(e^{\frac{4\pi}{c}f_i\left(R_0+\frac{L}{2}\cos(\omega t_i)\right)} + e^{\frac{4\pi}{c}f_i\left(R_0-\frac{L}{2}\cos(\omega t_i)\right)}\right) \tag{2}$$

where E_i is the signal acquired at frequency f_i, c is the speed of light, R_0 is the distance of the blade rotation centre from the radar, E_0 is a constant that depends on the instrument, L is the blade diameter, ω is the rotation speed of the blade. The signals of the four blades are summed, taking into account of the position ($R_{0,k}$) of each blade.

$$E_i = \sum_{k=1}^{4} E_0\left(e^{\frac{4\pi}{c}f_i\left(R_{0,k}+\frac{L}{2}\cos(\omega t_i+\varphi_k)\right)} + e^{\frac{4\pi}{c}f_i\left(R_{0,k}-\frac{L}{2}\cos(\omega t_i+\varphi_k)\right)}\right) \tag{3}$$

Finally, by calculating the IFFT of the simulated signal for a target at 500 m we obtain the plot in Fig. 3. It is evident that the effect of the blade movement can be see as multiple peaks inside a range interval cantered in the UAV position

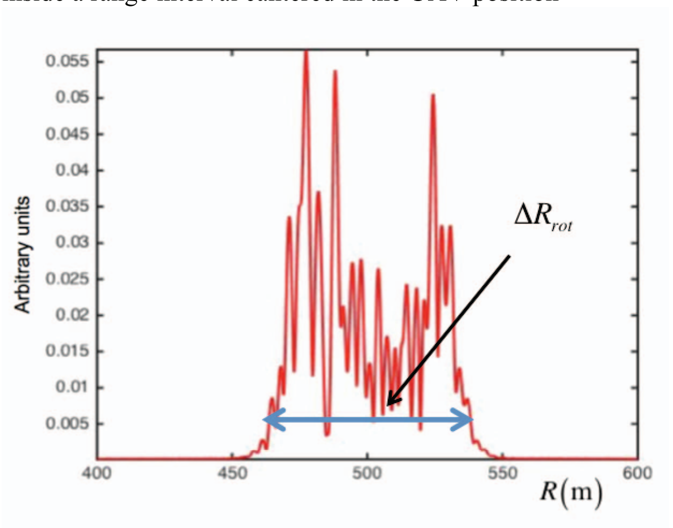

Fig. 3: Simulated signal

This range interval with good approximation is given by

$$\Delta R_{rot} = \frac{f_c}{B}\omega L\tau \tag{4}$$

In order to demonstrate eq. (4) we can refer to a single target moving to constant speed v. The backscatter signal is

$$E_i = E_0 e^{j\frac{4\pi}{c}(f_0+i\Delta f)(R_0+iv\Delta t)} \qquad -\frac{N_f}{2} \le i \le \frac{N_f}{2} \tag{5}$$

with $\Delta f = (\Delta t)B/\tau$. Eq. (5) becomes

$$E_i = e^{j\frac{4\pi}{c}\left(f_0R_0+if_0\frac{v\tau}{B}\Delta f+i\Delta fR_0+i^2(\Delta f)^2\frac{v\tau}{B}\right)} \tag{6}$$

If the last term in the argument of the exponential can be neglected, eq. (6) can be written as

$$E = e^{j\frac{4\pi}{c}\left(f_0R_0+(i\Delta f)\left(f_0\frac{v\tau}{B}+R_0\right)\right)} \tag{7}$$

On the other hand, if

$$v\tau << R_0\left(\frac{B}{f_0}\right) \tag{8}$$

eq. (7) can be written as

$$E = e^{j\frac{4\pi}{c}\left(f_0\left(f_0\frac{v\tau}{B}+R_0\right)+(i\Delta f)\left(f_0\frac{v\tau}{B}+R_0\right)\right)} \tag{9}$$

Therefore

$$E = e^{j\frac{4\pi}{c}\left((f_0+(i\Delta f))\left(f_0\frac{v\tau}{B}+R_0\right)\right)} \tag{10}$$

The IFFT of Eq. (9) is the sinc centred in

$$R = f_0\frac{v\tau}{B} + R_0 \tag{11}$$

Since the maximum linear speed of a rotating target is $\pm\omega L/2$, it results that the multiple peaks of a rotating blade must be inside the range interval given by the (4), that is what we had to demonstrate.

IV. Simulations

In order to simulate a realistic acquisition, we considered a quadcopter at distance R_0 = 100 m. The distance between the motors was 0.5 m, and the blade diameter 0.25 m. The rotation angle of the quadcopter axis was random. The initial phase of each blade was random. As signal we used the MTI (Moving Target Indicator) calculated as difference between two consecutive acquisitions. For estimating the range spread of the signal in time domain we selected a threshold equal to 40% of maximum. The radar parameters we used in simulation have been specified above. Fig. 4 resumes the obtained results. For each rotation speed we performed 10 simulations (with random rotation angle and blade phase) and we calculated the mean value and the standard deviation. In the plot the standard deviation of each set of 10 simulations is shown as an error bar. The full line represents the theoretical values of the range spread ΔR_{rot} given by (4).

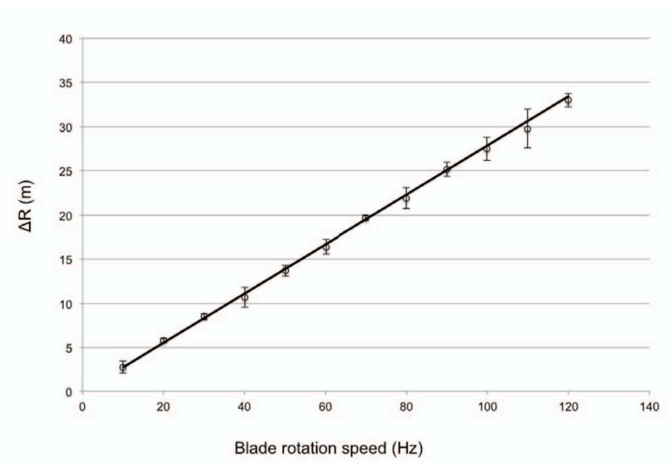

Fig. 4: Simulated results

The uncertainty of the method (even in simulation) is given by the intrinsically random composition of the contributions of each single moving scatter. In the simulated case the uncertainty in blade rotation estimation resulted of about 7% in the range 10 Hz - 120 Hz.

V. Experimental Test with a single rotating blade

In order to validate theory and simulation above reported we arranged the experimental set-up depicted in the picture in Fig. 5. A single metallic blade of 30 cm diameter was rotating using a motor. The rotation speed of the motor could be controlled with its power voltage. Blade and motor was positioned on the tip of a 4.7 m high pole. The CWSF radar was at 9.5 m from the basis of pole. So the distance radar-blade was 10.59 m.

Fig. 4: Experimental set-up

Fig. 5 shows a typical radar image we obtained. The rotation speed was 10.1 Hz . The range spread of the signal is between about 8 m and 13 m.

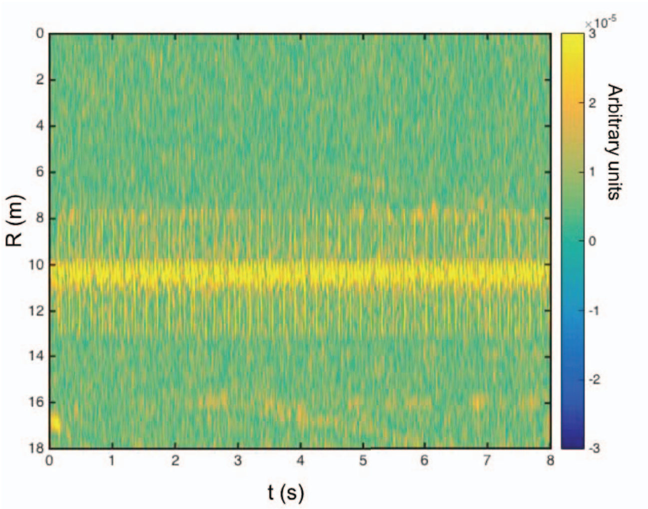

Fig. 5: Radar image of the rotating blade

For estimating the range spread due to the blade rotation, we summed along slow time (x-axis in Fig. 5) the absolute values of the signal, by obtaining the plot in Fig. 6. Finally the range spread is calculated by applying a threshold of 25% with respect to the maximum. The obtained range spread for plot in Fig. 6 has been 5.34 m, to be compared with the theoretical value 6.30 m given by eq. (4), where we have taken into account of the view direction that is not parallel to the rotation blade's plane.

We repeated the measurements by varying the blade rotation speed from 6.18Hz to 16.1 Hz. The plot in Fig. 7 resumes the obtained results. The dotted line is the expected theoretical value. The mean percentage error has been 11%.

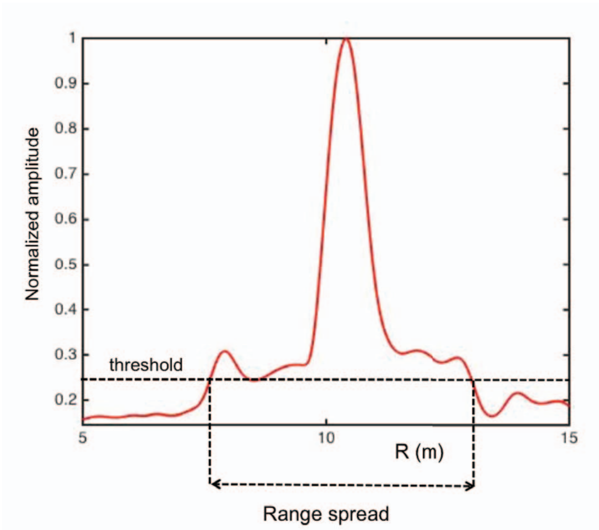

Fig. 6: Radar profile averaged along slow time

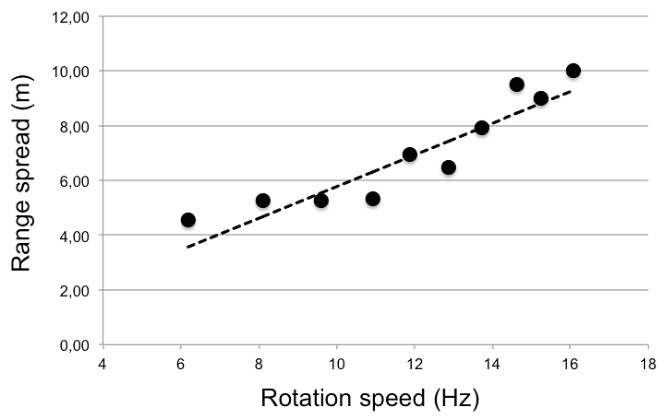

Fig. 7: Experimental results

VI. Tests with a flying UAV

A toy quadcopter (35 cm large with four plastic blades of 13 cm diameter disposed as shown in Fig. 8) was piloted in front of a CWSF radar operating with parameters specified above (the design details of the radar are reported in [7]).

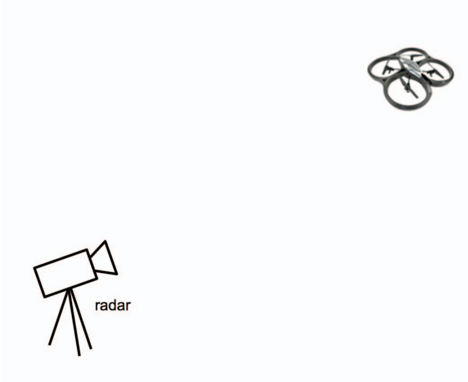

Fig. 8: Experimental test

Fig. 9 shows the obtained result. In the *y*-axis there is the range and in *x*-axis the time. The quadcopter appears as a discontinuous trace between 10 m and 20 m.

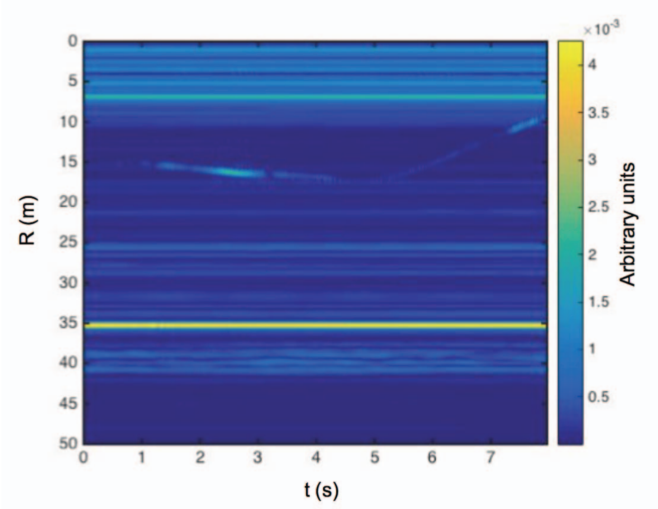

Fig. 9: Experimental radar image

By calculating the MTI (Moving Target Indicator) the static clutter is rejected and the quadcopter trace is well evident (Fig. 10).

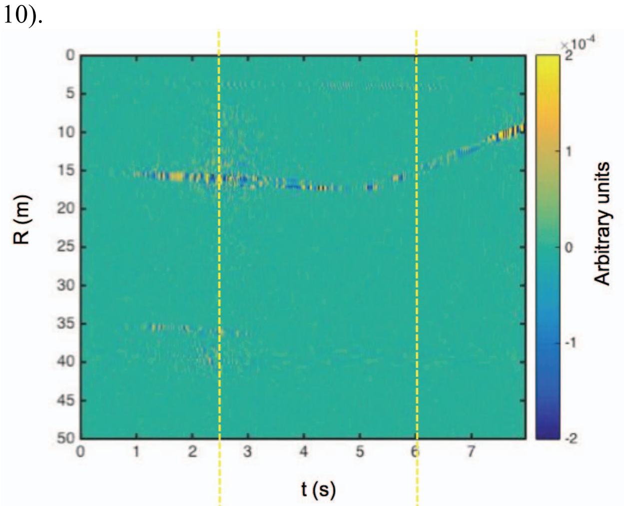

Fig. 10: MTI of radar image in Fig. 4

Fig. 11 shows the range plot at t = 2.5 s. Its shape is consistent with the theoretical model discussed above: the target appears as a set of multiple peaks inside a range interval cantered in the UAV position. The range spread of the target gives a rough estimation of the rotation speed of blades (if their size is known). In particular at t=2.5 s the rotation speed is 50 Hz, while at t = 6 s about 25 Hz (see Fig. 12). This is consistent with the fact that at 2.5 s the quadcopter was taking off, while at 6 s it was going down.

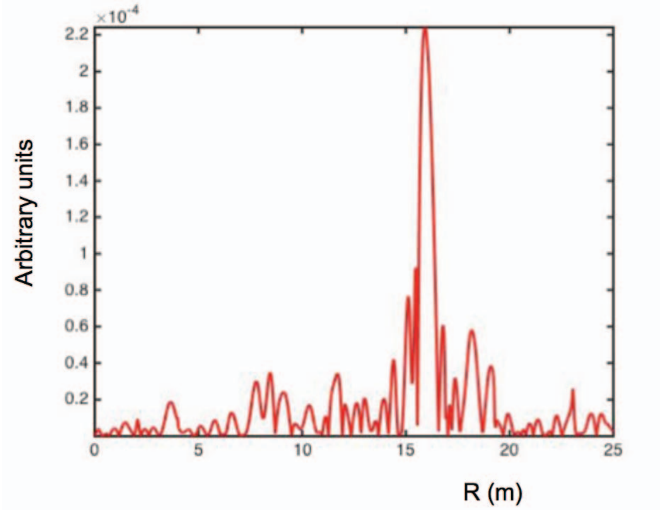

Fig. 11: Range plot at t=2.5

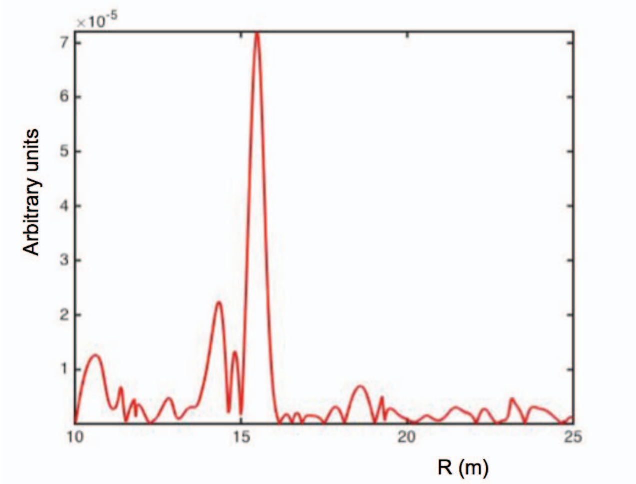

Fig. 12: Range plot at t=6.0

VII. CONCLUSION

In this paper the authors observed that the detection of rotating blades using CWSF radar, gives a sort of range spread of the signal proportional to the rotation speed of the blades. It suggests that we could use this spread for collecting information about the flying drone. Different UAV can have different rotation speeds, and the rotation speed changes during the manoeuvres (take off, landing…). Nevertheless it is worth to note that for a professional UAV the rotation speed can be so high that the spread could cover a too large range to be easily managed. As an example a blade of 0.13 m diameter at 100 Hz, spreads peaks on a range of about 28 m. It means that the signals of the blades of two UAV that are closer then 28 m are not separable. Furthermore, even for a single UAV, the range is so large that it is not easy to distinguish the peaks relative to the blade's motion from dynamic clutter due to different causes.

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